

Small Field Dosimetry

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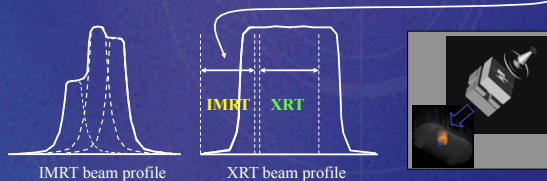
Conflict of Interest Statement:
Part-time consultant to Accuray

Outline

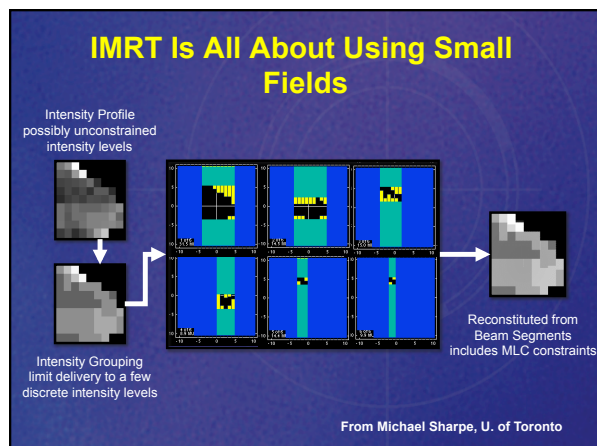
- Relevant to IMRT, SRS, and SBRT
- Main Small Field Dosimetry Issues
 - Charged Particle Equilibrium
 - Temporal Non-Constancy
 - Partial Volume Effects
 - Recombination/Charge Multiplication
- Calibration of Non-Standard Fields
 - IMRT as a Large Collection of Small Non-Standard Fields
 - IAEA Calibration Initiative for Non-Standard Fields

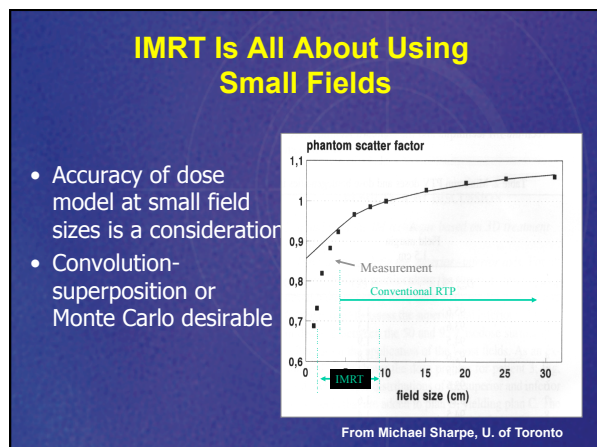
Model-Based Calculation Methods Are Need for IMRT Treatment Planning

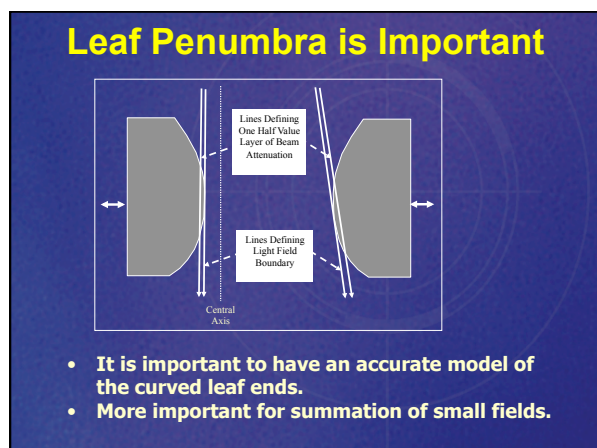
- IMRT = $\mathbf{I}$ small fields
- Dose = function(penumbra+leakage+head scatter)
- Need accurate treatment head model to get this right

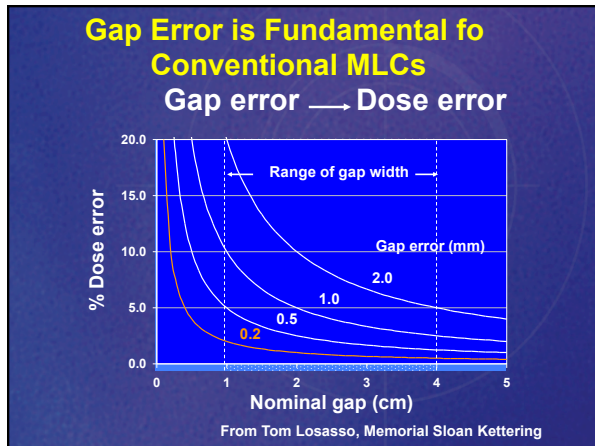


From Michael Sharpe, U. of Toronto

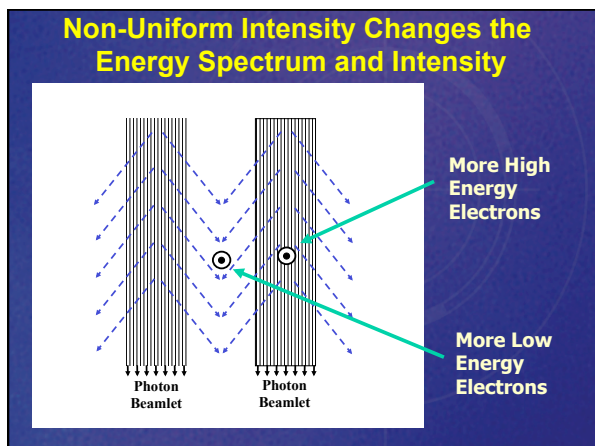






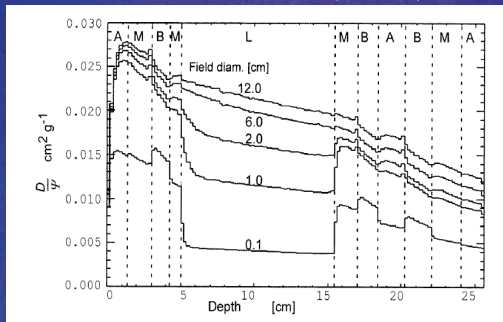


- ### Potential Dosimetry Issues
- Charged particle equilibrium
 - Different spectrum for collection of small fields
 - Non-uniform dose
 - Temporal non-constancy
 - A very small effect for ion chambers
 - May not be true for other dosimeters
 - Partial volume effect
 - Most important effect especially when measuring output factors for small fields
 - Perturbation effects for small chambers
 - Charge multiplication (failure of electronegative gas assumption)
 - Electron emission from electrodes



Dose per Incident Energy Fluence As a Function of Field Diameter

A=Adipose, M=Muscle, B=Bone, L=Lung 4 MV, Parallel Beam



Ahnesjö and Asparadakis, 1999 Phys Med Biol 44:R99-R155

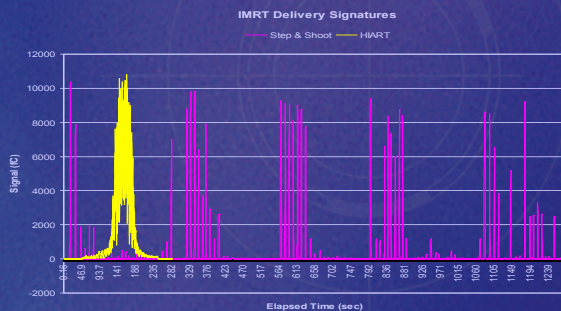
Change in Stopping Power Ratio

Comparison of Spencer-Attix ($\Delta=10$ keV) restricted mass collisional stopping powers ratios (water/air) at 5 cm depth in water for various 6 MV beams with stereotactic and MLC beams.

6 MV beams	Beam quality, TPR(20,10)	Andreo, (1994)	Sánchez-Doblado, (2003)	Column4/Column3
Elekta SL-18 10 x 10 cm ²	0.690	1.1187	1.1188	1.000
1.0 cm diameter stereo field			1.1155	0.997
0.3 cm diameter stereo field			1.1153	0.997
Siemens Primus 10 x 10 cm ²	0.677	1.1213	1.1221	1.001
2 x 2 cm ² irregular on-axis beamlet			1.1203	0.999
2 x 2 cm ² irregular 8 cm off-axis			1.1250	1.003

Temporal Delivery of IMRT

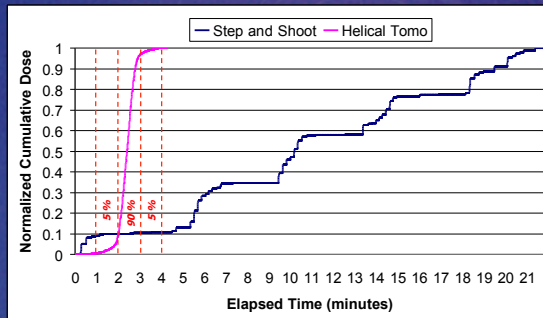
Delivery of Dose to a Single Voxel



From Tim Holmes, St. Agnes Baltimore

Temporal Delivery of IMRT

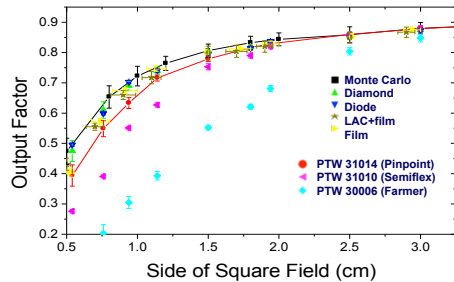
Delivery of Dose to a Single Voxel



From Tim Holmes, St. Agnes Baltimore

Partial Volume Effect

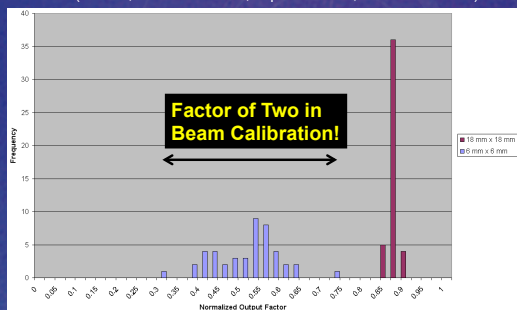
Dose to Water For Small Fields



From Roberto Capote, IAEA

High Uncertainty in Output Factors

Example: Statistics of 45 Output Factors for 6 mm and 18 mm square fields (Novalis, SSD = 1000 mm, depth = 50 mm, various detectors)



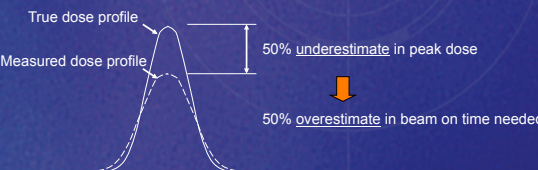
From Wolfgang Ullrich, BrainLab

The New York Times

Radiation Bills Raise Question of Supervision
 By WALT BOGDANICH and REBECCA R. RUIZ
 Published: February 25, 2010

Dose in 76 patients exceeded prescription by 50%
 Beam measurement error by physicist

Ion chamber  Detector too large – blurs measured dose profile for small beams



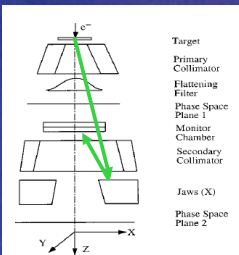
True dose profile
 Measured dose profile
 50% underestimate in peak dose
 50% overestimate in beam on time needed

Reasons for Drop in Output with Small Field Size

- Backscatter into monitor unit from beam defining jaws
- Reduced scatter (phantom and head)
- Electronic disequilibrium
- Obscuration of the source

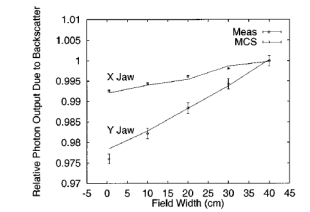
Backscatter into Monitor Chamber

The effect is due to backscattered photons entering the monitor and resulting in feedback to the linac to lower its output



Target
 Primary Collimator
 Flattening Filter
 Phase Space Plane 1
 Monitor Chamber
 Secondary Collimator
 Jaws (X)
 Phase Space Plane 2

Varian 2100 – 10 MV. Results with other jaw completely open



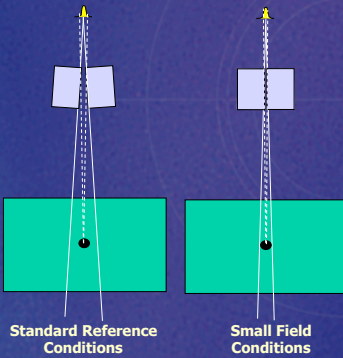
Relative Photon Output Due to Backscatter

Field Width (cm)

Y Jaw
 X Jaw
 Meas MCS

Liu et al.,
 Med. Phys 2000;27:737-744

Problems with Measuring Conventional Output Factors



- Small field openings obscure the source which is difficult to measure and error prone.
- Amount of phantom scatter changes as well as lateral disequilibrium.
- Partial volume effects can mask machine output factor.

Measured and MC Output Factor ($S_{c,p}$) as Function of Electron-Beam FWHM

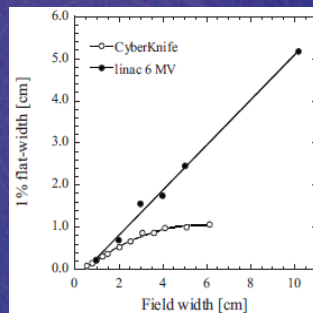
Point source assumption starts breaking down for small fields.

TABLE IV. Measured and MC-simulated $s_{c,p}$ for the four detectors and for the 5, 7.5, and 10 mm collimators, for the various FWHM of the Gaussian spatial distribution of the electron source.

		FWHM 1.4 mm	FWHM 1.8 mm	FWHM 2.2 mm	FWHM 2.6 mm
Coll 5 mm	Measured $s_{c,p}$	Simulated $s_{c,p}$	Simulated $s_{c,p}$	Simulated $s_{c,p}$	Simulated $s_{c,p}$
A16	0.614	0.669	0.643	0.611	0.585
PinPoint	0.613	0.661	0.636	0.607	0.582
Diode	0.710	0.757	0.732	0.704	0.679
Diamond	0.613	0.677	0.639	0.609	0.580
Coll 7.5 mm					
A16	0.801	0.809	0.808	0.799	0.792
PinPoint	0.798	0.805	0.802	0.795	0.789
Diode	0.852	0.757	0.850	0.843	0.842
Diamond	0.815	0.833	0.818	0.813	0.803
Coll 10 mm					
A16	0.859	0.874	0.870	0.860	0.857
PinPoint	0.858	0.867	0.865	0.860	0.857
Diode	0.895	0.909	0.896	0.890	0.886
Diamond	0.871	0.889	0.876	0.872	0.866

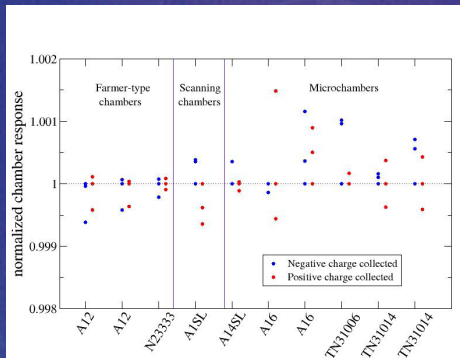
Chamber Selection For Beams without Field Flattening Filters

- Dose flatness insufficient for Farmer-type chamber
- Cavity length should not be greater than 1 cm
- Option: cross calibrate a short chamber with Farmer-type chamber



Kawachi et al, Med Phys (2008) 4591

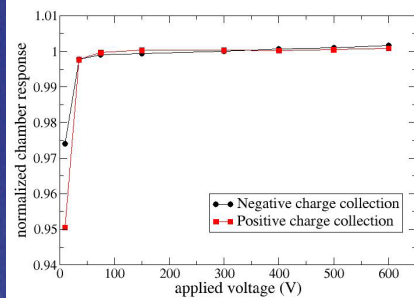
Normalized Chamber Response



Courtesy Jessica Snow and Larry DeWerd, UW ADCL

PTW N23333

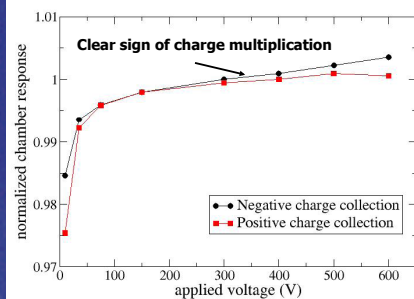
0.6 cc



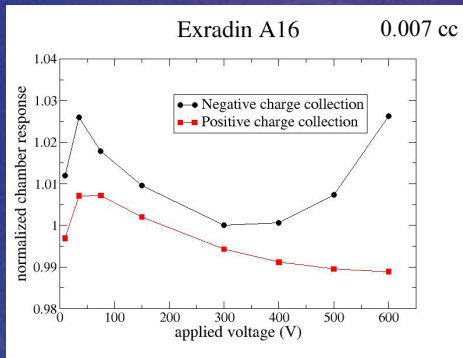
Courtesy Jessica Snow and Larry DeWerd, UW ADCL

Exradin A1SL

0.057 cc



Courtesy Jessica Snow and Larry DeWerd, UW ADCL



Courtesy Jessica Snow and Larry DeWerd, UW ADCL

Which physical effects results in the greatest perturbation for small field dosimetry for ion chambers?

Pick One:

- 26% 1. Charged particle disequilibrium
- 23% 2. Temporal non-constancy
- 26% 3. Partial volume effects
- 25% 4. Recombination/charge multiplication effects

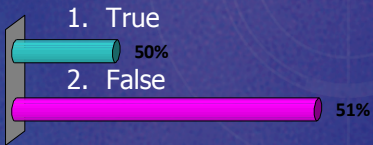
Which physical effects results in the greatest perturbation for small field dosimetry for ion chambers?

Pick One:

- 1. Charged particle disequilibrium
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True or False?

Small field dosimetry is important for good quality assurance, but typical inaccuracies encountered can never put patients at grave harm.

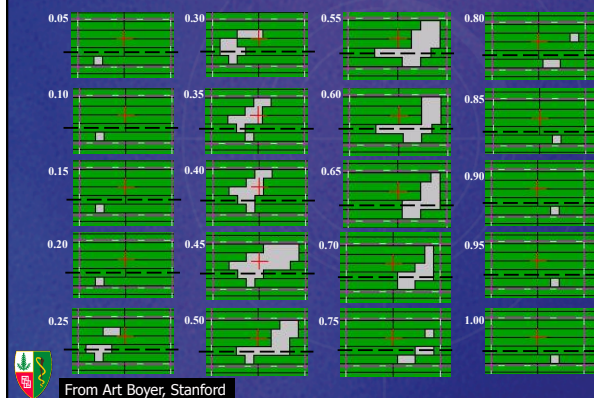


True or False?

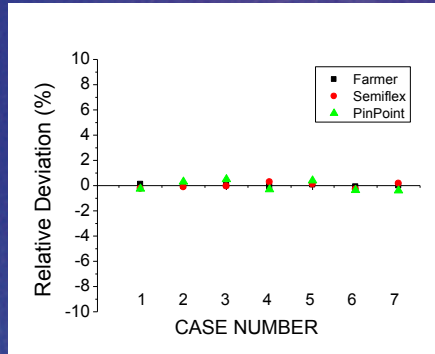
Small field dosimetry is important for good quality assurance, but typical inaccuracies encountered can never put patients at grave harm.

1. True
 2. False
2. False: Output factors for the smallest fields are difficult to measure and can change the dose the patient receives by many 10s of percent

IMRT Is Far from Reference Conditions

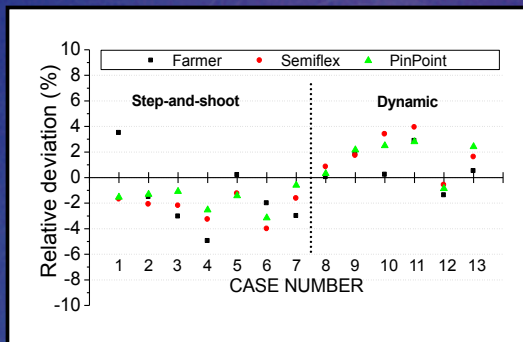


Audit for TRS 398 Reference Dosimetry



From Roberto Capote, IAEA

IMRT Audit



Sánchez-Doblado F, Hartmann G., Pena J., Capote R. *et al*
IJROBP 68 (2007) 301-310

IAEA/AAPM Meeting for the Dosimetry Code of Practice: Small Fields and Novel Beams

Outside Participants

- Jan Seuntjens
- Hugo Palmans
- Karen Rosser
- Saiful Huq
- Wolfgang Ullrich
- Warren Kilby
- Rock Mackie

IAEA

- Pedro Andreo
- Ken R. Shortt
- Stanislav Vatnitskiy
- Roberto Capote
- Joanna Izewska
- Ahmed Meghzifene
- Rodolfo Alfonso

Alfonso et al., A new formalism for reference dosimetry in small and non-standard fields, *Med. Phys.* 35: 5179 (2008)

Examples of Small and Novel Fields

- GammaKnife - 1.8 cm diameter collimator (1.6 cm on the Perfexon) is the largest collimator – intrinsically composite field – not 100 cm SSD
- Linac SRS beams - extrapolate to small field conditions
- Accuray - 6 cm diameter collimator is the largest collimator – no field flattening filter
- TomoTherapy - 5 cm is the largest slice width – no field flattening filter
- IMRT - made up of numerous small fields

IAEA TRS-398 & TG-51 Nomenclature

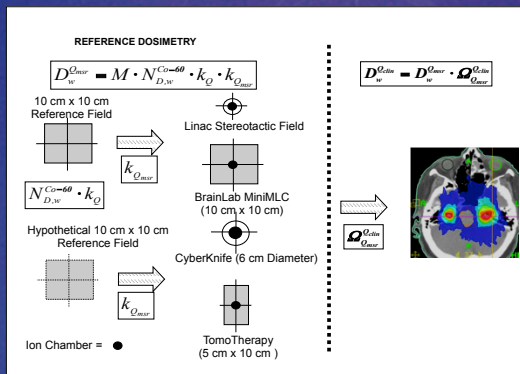
IAEA TRS-398

$$D_{w,Q_{msr}}^{f_{msr}} = M_{Q_{msr}}^{f_{msr}} \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \cdot k_{Q_{msr},Q}^{f_{msr},f_{ref}}$$

IAEA TG-51

$$D_w^{Q_{msr}} = M \cdot N_{D,w}^{Co-60} \cdot k_Q \cdot k_{Q_{msr}}$$

Overview of Static Field Dosimetry

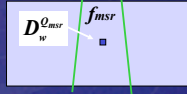


Static Field Calibration

Uses a machine-specific reference field, f_{msr}

$$D_w^{Q_{msr}} = M \cdot N_{D,w}^{Co-60} \cdot k_Q \cdot k_{Q_{msr}}$$

$$k_{Q_{msr}} = \frac{(D/M)_w^{Q_{msr}}}{(D/M)_w^Q}$$



Corrects for the differences between the conditions of field size, geometry, and beam quality of the conventional reference field and the machine-specific reference field.

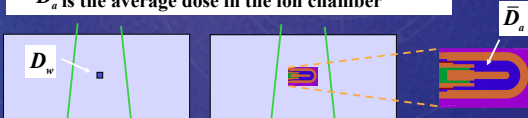
Calculate Using MC

Using method of Sempau et al 2004 *PMB* 49:4427-44

$$k_{Q_{msr}} = \frac{(D_w / \bar{D}_a)^{Q_{msr}}}{(D_w / \bar{D}_a)^Q}$$

D_w is the dose at the reference point in water

$\bar{D}_a$ is the average dose in the ion chamber



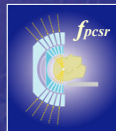
Adapted from Edmond Sterpin

Composite Field Calibration

Uses a plan-class specific reference field, f_{pcsr}

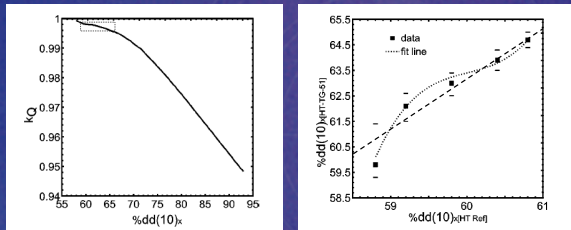
$$D_w^{Q_{pcsr}} = M \cdot N_{D,w}^{Co-60} \cdot k_Q \cdot k_{Q_{pcsr}}$$

$$k_{Q_{pcsr}} = \frac{(D/M)_w^{Q_{pcsr}}}{(D/M)_w^Q}$$



Corrects for the differences between the conditions of field size, geometry, and beam quality of the conventional reference field and the plan-class specific reference field.

“Effective k_Q ” for Tomo



1. Determine the $\%dd(10)_{HT Ref}$ for a tomotherapy unit for a 5 cm x 10 cm field at 85 cm SSD.
2. Using the graph at the right look up the value of $\%dd(10)_{HT TG-51}$.
3. Using the graph on the left and the derived value $\%dd(10)_{HT TG-51}$ determine the abscissa and this effective k_Q value is then called $k_Q \cdot k_{Q_{eff}}$ in the IAEA protocol.

Thomas et al (2005)

Static and Composite Field Calculations for Tomo

Static Field Calibration
(Section III.A.1)

Jeraj et al 2005

	$k_{Q_{msr}}$
5 cm x 10 cm	0.997
2 cm x 10 cm	0.993
2 cm x 2 cm	0.990

Composite Field Calibration
(Section III.A.2)

Duane et al 2006

	$k_{Q_{pcsr}}$
Unmodulated Helical Delivery 5 cm Slice Width	1.000
Unmodulated Helical Delivery 2.5 cm Slice Width	1.000
Unmodulated Helical Delivery 1 cm Slice Width	0.997

TomoTherapy: Static Field $k_{Qeff} = k_Q \times k_{Q_{msr}}$

(Standard Uncertainty)	Other References (10 cm x 5 cm)	Sterpin et al. (10 cm x 5 cm)
Exradin A1SL	0.997 (+/- 0.001)	0.996 (+/- 0.002)
Exradin A12 Farmer	1.000 (+/- 0.003)	1.001 (+/- 0.004)
PTW-31014 Pinpoint	0.992 (+/- 0.003)	0.993 (+/- 0.002)
PTW-31010 Semiflex	0.996	0.995 (+/- 0.002)
PTW-31006 Farmer	0.995	0.997 (+/- 0.002)
PTW-31018 (MicroLion)		0.993 (+/- 0.002)
NE2571	0.995	0.997 (+/- 0.002)

Sterpin et al. Med. Phys. 39 (7), July 2012

Two 6 MV Linacs: Nearly Same $K_{Qeff} = K_Q \times K_{Qmsr}$

	TomoTherapy	CyberKnife
Exradin A12 (0.65 cc)	1.001	1.006
NE2571 (0.67 cc)	0.997	1.003
Exradin A1SL (0.057 cc)	0.996	0.997

To within about a half percent, TomoTherapy and CyberKnife are like “Co-60 units”.

Pantellis *et al.* Med. Phys. 39 (8), August 2012, 4875-4885

On the output factor measurements of the CyberKnife iris collimator small fields: Experimental determination of the $k_{Q_{eff}}^{L_{dyn} \times f_{msr}}$ correction factors for microchamber and diode detectors

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Which is more correct? The IAEA and the AAPM are:

- 25% 1. Developing an entirely new dosimetry protocol to handle small fields.
- 25% 2. Fundamentally modifying the TG-51 or IAEA protocols to be applicable for small fields.
- 25% 3. Providing a methodology to obtain an appropriate calibration factor correction that is applicable for small fields.
- 26% 4. Wringing their hands, unable to act.

Which is more correct? The IAEA and the AAPM are:

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3. Providing a methodology to obtain an appropriate calibration factor correction that is applicable for small fields.
4. Wringing their hands, unable to act.

Conclusions

- IMRT, SRS and SBRT uses complex field boundaries and/or one or many small circular fields.
- Partial volume effects can result in severe error in output factor measurements.
- Small chambers exhibit unusual charge collection behavior.
- IMRT deliveries are far from the measurement conditions of calibration.
- IAEA/AAPM has developed a formalism to account for small and novel beams in more realistic beam conditions.
